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NASA Technical Memorandum 83131

DISPERSION OF FLAMMABLE CLOUDS RESULTING FROM LARGE SPILLS OF LIQUID HYDROGEN

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MAY 1981

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83131		
4. Title and Subtitle: DISPERSION OF FLAMMABLE CLOUDS RESULTING FROM LARGE SPILLS OF LIQUID HYDROGEN		5. Report Date: May 1981
		6. Performing Organization Code: 505-31-70-01
7. Author(s): Robert D. Witcofski		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address: NASA Langley Research Center, Hampton, Virginia 23665		11. Contract or Grant No.
		13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D. C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Collateral publication of a paper to be presented at the 16th Intersociety Energy Conversion Engineering Conference, Altanta, Georgia, August 9-14, 1981.

16. Abstract

The purpose of this paper is to report the preliminary findings of hydrogen vapor cloud dispersion experiments conducted by NASA. The experiments were performed to obtain basic information regarding the physical phenomena governing the dispersion of flammable clouds formed as the result of spills of large quantities of liquid hydrogen. The experiments consisted of ground spills of up to 5.7 cubic meters (1500 gal) of liquid hydrogen, with spill durations of approximately 35 seconds. Instrumented towers, located downwind of the spill site, gather data on the temperature, hydrogen concentration, and turbulence levels as the hydrogen vapor cloud drifted downwind. Visual phenomena were recorded by motion picture and still cameras. Preliminary results of the experiments indicate that, for rapid spills, thermal and momentum induced turbulences cause the cloud to disperse to safe concentration levels and become positively buoyant long before mixing due to normal atmospheric turbulence becomes a major factor.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Liquid Hydrogen, Spills, Safety, Cloud Dispersion, Flammable, Experimental, Cryogenic, Turbulence, Buoyancy	Unclassified - Unlimited Subject Category 28

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	9	A02

N-305

For sale by the National Technical Information Service, Springfield, Virginia 22161

Dispersion of Flammable Vapor Clouds Resulting from Large Spills of Liquid Hydrogen

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ABSTRACT

The purpose of this paper is to report the preliminary findings of hydrogen vapor cloud dispersion experiments conducted by NASA. The experiments were performed to obtain basic information regarding the physical phenomena governing the dispersion of flammable clouds formed as the result of spills of large quantities of liquid hydrogen. The experiments consisted of ground spills of up to 5.7 cubic meters (1500 gal) of liquid hydrogen, with spill durations of approximately 35 seconds. Instrumented towers, located downwind of the spill site, gather data on the temperature, hydrogen concentration, and turbulence levels as the hydrogen vapor cloud drifted downwind. Visual phenomena were recorded by motion picture and still cameras. Preliminary results of the experiments indicate that, for rapid spills, thermal and momentum induced turbulences cause the cloud to disperse to safe concentration levels and become positively buoyant long before mixing due to normal atmospheric turbulence becomes a major factor.

INTRODUCTION

Besides its use as a prime propellant for spacecraft, liquid hydrogen is distributed commercially for a variety of applications and has been identified as a promising future alternative aviation fuel. A somewhat unknown factor regarding its use is of that the consequences of an accidental release of a relatively large quantity of the fuel. Key factors in the assessment of the hazards associated with liquid hydrogen spills are the location, size, and concentration of the subsequently formed vapor cloud. It is generally accepted that the liquid will vaporize and as the hydrogen vapors are mixed with ambient air and warmed, the cloud will rise and diffuse to a concentration below the lower flammability limit of hydrogen. What is not known is the time history of the cloud until it diffuses to concentrations which are no longer hazardous. Before models can be developed to describe cloud behavior, a basic understanding of the physical phenomena which govern cloud behavior is required.

A series of hydrogen vapor cloud dispersion experiments have been conducted at NASA's White Sands Test Facility in New Mexico. The purpose of the experiments was to obtain basic information pertaining to the generation and dispersion of flammable clouds formed as a result of large rapid spills of liquid hydrogen, the type of spill which might occur as the result of the rupture of a large storage facility. The experiments consisted of ground spills of up to 5.7 m^3 of liquid hydrogen, with spill durations of approximately 35 seconds. Prolonged spill durations were also investigaged. Instrumented towers, located downwind of the spill site, gathered data on the temperature, hydrogen concentration, and turbulence levels as the hydrogen vapor cloud drifted downwind. Visual phenomena were recorded by motion picture and still cameras. The results of these experiments are believed to represent the first significant source of quantitative data regarding the dispersion of flammable clouds formed by large spills of liquid hydrogen. Data from the experiments has not been thoroughly analyzed, and the results presented herein are based upon initial analyses of the data.

APPARATUS AND PROCEDURE

Experimental Facility

It would have been desirable, from the standpoint of observing spill size effects, to instantly dump various quantities of liquid hydrogen (LH_2) onto the ground, but funding limitations precluded the construction of a large Dewar capable of doing so with adequate safety. A 5.7 m^3 (1500 gallon) Dewar (see fig 1) was borrowed from the Los Alamos Scientific Laboratory. A 10.2 cm diameter line was extended from an access hatch in the top to a location close to the bottom of the Dewar. A valve provided a transition from the 10.2 cm line to a 15.2 cm internal diameter foam-insulated line approximately 30 m long. Two 22.7 m^3 liquid hydrogen trailers provided storage capacity for the experiments. Prior to each test, the 5.7 m^3 spill Dewar and 30 m line were filled with liquid hydrogen. To conduct a spill, gaseous helium pressurized the spill Dewar to as much as 690 kPa. A valve at the end of the spill line was opened and the liquid hydrogen was expelled out through the 30 m spill line. For the rapid type spills, the 5.7 m^3 were expelled in approximately 35 seconds. The spill line dumped the liquid hydrogen into a 9.1 m diameter spill pond (see fig 2). The spill pond was constructed of earthen sides approximatley 0.6 m high with compacted sand as a bottom. A 1.2 by 1.2 m steel plate, 1.27 cm thick, was located directly under the line exit to preclude earth erosion. In order to minimize the momentum associated with the liquid hydrogen jet impact, a diffuser was added after the first spill experiment.

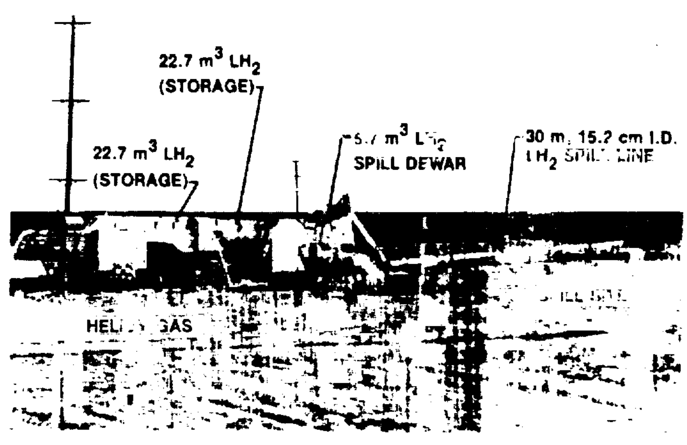

Figure 1.- Liquid hydrogen spill facility.

Instrumentation

Nine 19.5 m towers were deployed downwind of the spill pond, as shown in figure 3, and the cloud diagnostics instrumentation was mounted on the towers.

Cloud sampling bottles were mounted in clusters of eight (fig 4) at 1 m, 9.4 m, and 18.6 m heights. The sampling bottles were 500 ml spherical stainless bottles equipped with spark-proof solenoid valves. Prior to each experiment, the bottles were evacuated to 133 Pa. During the experiments, the bottles were opened individually for a period of one second, at predetermined time intervals. After each experiment, the sampling bottles were removed from the test site and the contents of the bottles were analyzed on gas chromatographs to provide a quantitative time history of the hydrogen concentration in the cloud as it drifted through the instrumentation towers. The sampling bottles were also a means of determining any variations in the constituency of the air, such as water vapor, and the nitrogen-oxygen balance.

Three hydrogen sensors were located on each tower at 1 m, 9.4 m, and 18.6 m levels. The sensors consisted of a wheatstone bridge, one arm of which was coated with a catalyst which reacts with hydrogen, producing a temperature increase, a resistance imbalance, and a voltage output which was a function of the hydrogen concentration. The sensors were temperature compensated and were fitted with flame arrestors to preclude cloud ignition by the sensors. It has been estimated that there was an approximate two second delay from the time the hydrogen reached the sensor until the sensor reacted. These sensors were quite accurate for hydrogen concentrations up to about 4 percent, but prolonged exposure to concentrations above 6 or 8 percent could saturate the catalyst. Thus, the sensor output was meaningful only at low hydrogen concentrations near the lower flammability limit of hydrogen. The sensors were used primarily to determine when a flammable cloud was present, but they were also used on occasion to trigger the initiation of the opening of the sampling bottles.

Thermocouples were deployed at 3 m intervals on each tower. The tower mounted thermocouple data are planned for use as indirect hydrogen concentration indicators (this implies adiabatic mixing of hydrogen and air).

Each of the three center towers, at 9.1 m, 18.3 m, and 36.6 m radii from the center of the spill pond, was instrumented with two UVW turbulence indicators. The UVW indicators consist of three propellers, whose axes have been arranged in three orthogonal directions. The speed of each propeller was calibrated and correlated with the component of the wind velocity parallel to its axis. The instrument provided a time history of the three components of wind velocity. These components were used in calculating the wind speed, aximuth and elevation, for pretest, test (including inside the cloud), and post-test conditions.

Meteorological data was obtained prior to, during, and after each experiment. The meteorological instrumentation was located on towers around the test site, and on a meteorological balloon which was flown at varying altitudes upwind of the test site. A major purpose of the balloon-mounted meteoroligical package was to determine whether atmospheric temperature inversions were present during the experiments. Data obtained included temperature, humidity, barometric pressure, and wind speed and direction.

Each test was recorded by both still and motion picture cameras. The still photographs were taken from a point 393 m from the spill site and approximately 65 degrees to the wind. The motion pictures were taken from points approximately perpendicular to the wind, looking directly downwind, and from a helicopter approximately 0.8 km above and upwind of the test site.

Figure 2.- Liquid hydrogen spill line, valve, spill pond, and diffuser.

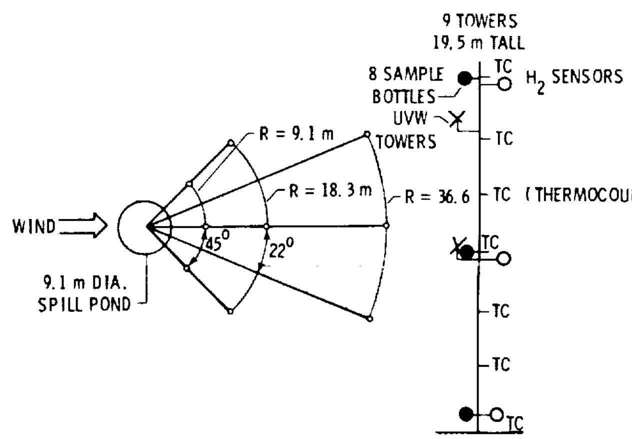

Figure 3.- Deployment of instrumentation towers and typical tower instrumentation array.

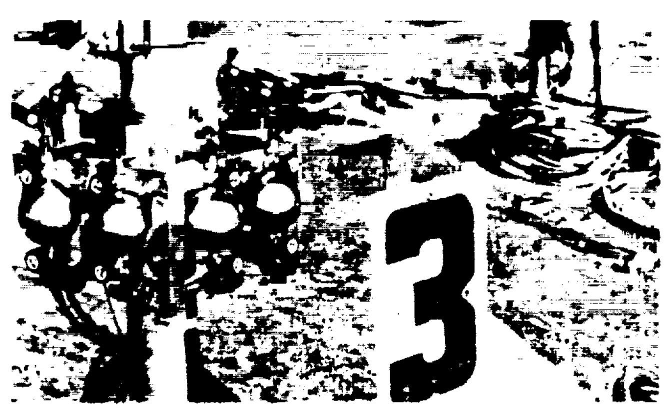

Figure 4.- Hydrogen vapor cloud sampling bottle cluster.

Methods and Procedures

Prior to the conduct of each experiment, short term meteorological forecasts were utilized to identify a potential test window within a period of a few days. The spill Dewar was loaded with liquid hydrogen and the countdown for a spill was initiated. If favorable meteorological conditions did not develop (wind direction wrong) as the day progressed, the countdown was aborted, and the spill was attempted the following day. This procedure continued until either a spill was conducted or the boil-off losses precluded the conduct of a spill. Just prior to each spill experiment, a smoke grenade was used to verify that the local wind direction was suitable for conduct of a spill.

The sequence was completely automated for the operation of the spill facility, triggering of the instrumentation, and data acquisition systems. Data collected during the test was stored on a disc for future analysis.

RESULTS AND DISCUSSION

Seven liquid hydrogen spill experiments were conducted. No attempt was made to ignite the spills and no spills ignited. The spill quantities, spill times, meteorological conditions, and types of data obtained during each experiment are listed in Table 1. Test 1 was conducted in order to gain a degree of familiarity with the spill facility and the data acquisition system, and to provide insight into the placement of the instrumentation towers for the tests which were to follow. Only limited instrumentation was deployed for Test 1, and most of that instrumentation was located at or very near the edge of the spill pond. Tests 3 and 7 were intentionally conducted at relatively slow spill rates in order to gain insight in the role of spill rate and spill dynamics in cloud dispersion. Tests 2, 4, 5, and 6 are the tests which are of primary interest since the spill time for these tests was quite short, thus providing the highest spill rates, one of the goals of the experiments. The enormous quantity of data obtained from the experiments precludes its complete inclusion in this paper; however, some samples of the data from a typical test are presented.

TABLE 1.- RECENTLY COMPLETED 5.7 M^3 LIQUID HYDROGEN SPILL EXPERIMENTS, INCLUDING SPILL TIMES, METOEROLIGICAL CONDITIONS AND DATA OBTAINED

Test No. and date (1980)	Spill time (sec)	Windspeed (m/s)	Ambient temp., °C	Relative humidity, %	Data obtained: Motion picture	Sample bottles	Thermo-couples	Turbu-lence	H_2 sensors	Still photos
(1) Aug. 1	60	2.7-3.1	33	16	X	Very near spill pond only				X
(2) Sept. 25	40	1.3-1.8	25	50	X	X	X	X	X	X
(3) Oct. 10	85	4.5	26	27	X			X		
(4) Oct. 22	33	3.1-3.6	19	27	X	X	X	X	X	X
(5) Nov. 24	24	6.3	12	43	X	X	X	X	X	X
(6) Dec. 18	35	2.2	25	29	X	X	X	X	X	X
*(7) Dec. 18	240	3.1	22	21	X		X	X	X	X

*2.8 m^3

Concentrations

Table 2 contains examples of the sample bottle data obtained from Test 2, from a tower located 9.1 m from the center of the spill pond (i. e. 4.6 m from the edge of the spill pond). In the table is shown the height of the 3 bottle clusters on the tower and the time, in seconds, after the start of the spill at which the samples were taken. The data shown are the hydrogen

TABLE 2.- EXAMPLE OF HYDROGEN CONCENTRATIONS OBTAINED FROM SAMPLE BOTTLES FROM TEST 2 AT A 9.1 m RADIUS TOWER

		TIME SEQUENCE, SECONDS							
		4.7	17.1	28.7	40.1	51.5	63.1	75.3	86.9
HEIGHT	BOTTLE	PERCENT HYDROGEN							
1 m	1 2 3 4 5 6 7 8	0	0.6	0.002	0.082	.001	.001	.001	0
9.4 m	1 2 3 4 5 6 7 8	0.015	18.7	22.3	19.9	0.018	0.004	0	0
18.6 m	1 2 3 4 5 6 7 8		13.3	0.022	0.002	0	0	0	0

concentrations, by volume percent. Observation of the data indicates that the flammable (1, 2) cloud (4 percent hydrogen for an upward burning flame and 8 to 9 percent for any direction) passed above the 1 m level, and intercepted the 9.4 m level of bottles. Whereas flammable concentrations were measured at the 9.4 m level from 17.1 seconds to 40.1 seconds, flammable concentrations were measured at the 18.6 m level only at a time of 17.1 seconds. The flammable cloud passed through the 18.6 m level early in the experiment primarily because the momentum of the hydrogen spill was greater during the first few seconds of the test than later in the test, thus causing the first part of the spill to "bounce." The momentum of the hydrogen spill was greater during the first few seconds because when the valve at the end of the spill line opened, the pressure in the spill line and spill Dewar dropped, and the helium pressurization system in the spill Dewar was unable to reestablish the initial spill Dewar pressure. In addition, there was a slight misalignment between the spill line and the spill pond diffuser. When the valve at the end of the spill line was opened, the momentum of the liquid hydrogen caused the line to lift up slightly, thus aggravating the misalignment problem, and allowing the hydrogen to impact the ground more directly, accentuating the "bounce" of the hydrogen due to its momentum.

Data from both the hydrogen sensors and the sample bottles are shown in figure 5 for the same test and tower. The coordinates are tower height, hydrogen concentration, and test time. Recall that while the sample bottles were capable of measuring any hydrogen concentrations present, the hydrogen sensors were useful for measuring hydrogen concentrations up to only 4 or 6 percent, and that there was a delay in the response of the sensors. These factors considered, good correlation is seen to exist between the two data sources. The fact that the sensor at the 18.6 m level of the tower indicated a 2 to 5 percent hydrogen concentration while the second sample bottle collected no significant quantity of hydrogen, can probably be attributed to the slow response time of the sensor, and the violent fluctuation in hydrogen concentration as

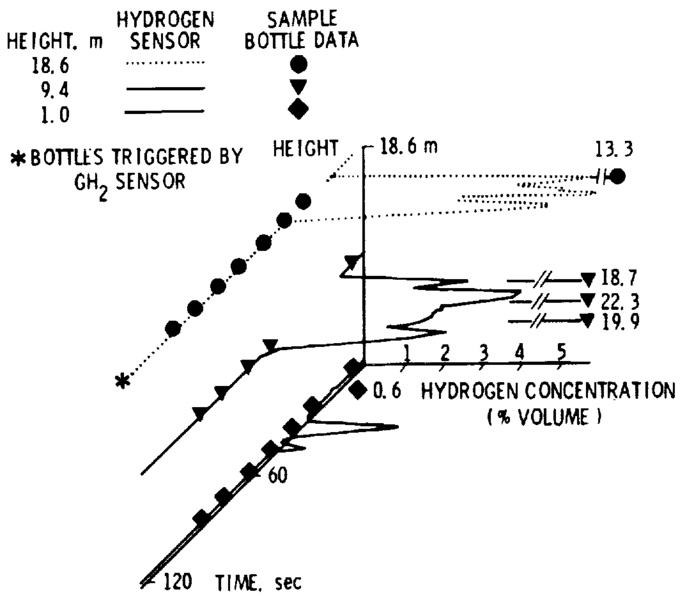

Figure 5.- Time history of hydrogen concentrations as measured by both hydrogen sensors and sample bottles for Test 2 at a 9.1 m radius tower.

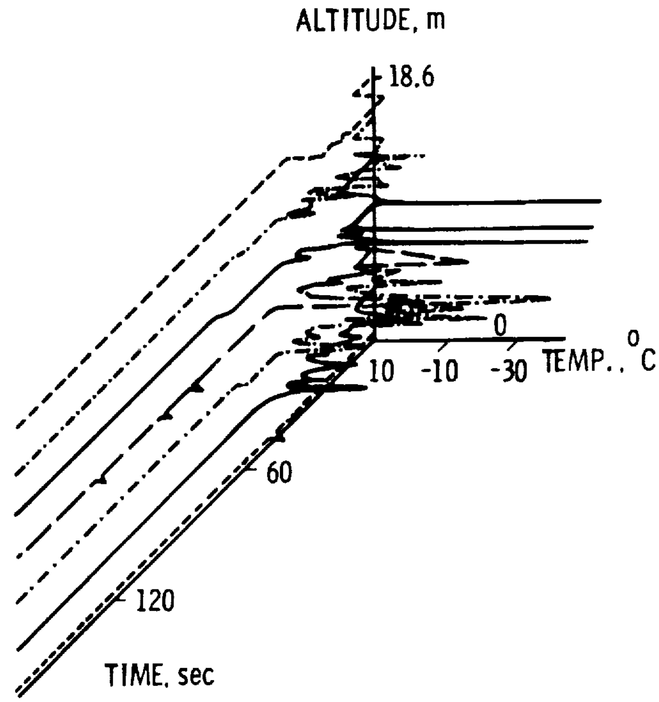

Figure 6.- Temperature history for Test 2 at a 9.1 m radius tower.

depicted by the thermocouple data discussed in the next section.

No variation was found in the constituency of the air which was mixed with the hydrogen samples taken. That is to say, the water vapor content and the oxygen-nitrogen balance of the air was consistent with that of the ambient air. This was observed even for the highest hydrogen concentrations captured by the sampling bottles, 78 percent by volume, which was obtained at the very edge of the spill pond during Test 1.

Temperatures

The temperature history at various heights for the tower from which the bottle samples and sensors of table 2 and figure 5 were obtained is shown in figure 6. The vertical axis is the tower height, the horizontal axis is the temperature, and the remaining axis test time. Lower temperatures indicate greater hydrogen concentrations. The temperature data of figure 6 indicate that the higher hydrogen concentration portion of the cloud passed through approximately the middle height of the tower. The temperature data are currently being utilized to deduce, through adiabatic mixing calculations, the hydrogen concentrations as a function of time. The temperature data, because of the large number of thermocouples and the fast response time of the thermocouples, will likely prove to be a most valuable source of cloud concentration data.

Turbulence

UVW indicators were not located on the tower from which the previously discussed data were taken, but an adjacent tower (center tower, 9.1 m radius) was instrumented with two UVW indicators at heights of 2 m and 7 m. The calculated wind speed, azimuth, and elevation angle are shown in figure 7 as a function of time. Notice that the traces were obtained from -120 to +120 seconds, taking the origin of time at the start of the test. The traces before the start of the test show the structure of the turbulence as well as the wind mean speed

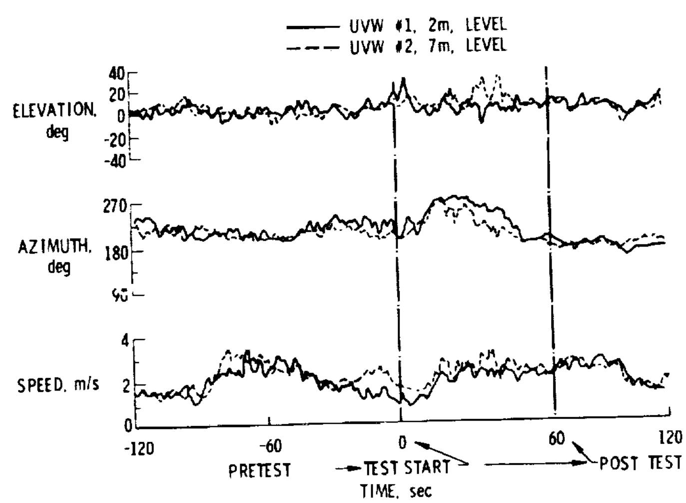

Figure 7.- Wind and cloud speed, azimuth and elevation, as calculated from UVW measurements from Test 2, at 2 m and 7 m heights of a 9.1 m radius tower.

and variability. The approximate time at which the visible cloud disappeared (post test time) is indicated. An inspection of the figure shows that the hydrogen vapor cloud had an effect on the azimuth; that is, a rotation of the wind velocity vector changed from 180 degrees to 270 degrees on both UVWs.

The elevation angle (angle between the resultant vector of the wind or cloud velocity and horizontal) of the cloud is depicted first by the upward deflection measured by the UVW located at a height of 2 m, and later by upward deflections measured by the UVW located at a height of 7 meters. Since the UVW instruments are momentum sensitive, and since the density of the cloud was reduced by the presence of the hydrogen, the true meaningfulness of the data from these instruments must await further analyses which utilize other sources of data obtained during the experiments.

Photographic

The visible cloud observed during a liquid hydrogen spill is actually condensed atmospheric water vapor. If one assumes adiabatic mixing of ambient air and hydrogen vapors at the normal boiling point, one can calculate the equilibrium temperatures of various hydrogen-air concentrations. Assuming that the temperature at the edge of the visible cloud is the dew point temperature, one can deduce the hydrogen concentration at the edge. Preliminary calculations have indicated that for the experiments reported herein, the edge of the visible cloud was at or quite near what is generally accepted to be the lower flammability limit of hydrogen-air mixtures for flame propagation in all directions (8 or 9 percent hydrogen, by volume). Figure 8 is a composite of still photographs from Test 4, during which the wind speed was about 3.6 m/s. With the exception of the photo of the test site, the photographs were taken at a point which was 393 m from the spill site and at an angle of 65 degrees to the wind. As a frame of reference, the dark tower to the right of the metal building in the photo is a meteorological tower, and corresponds to a downwind distance of about 30 meters from the spill site. The approximate times, after the start of the spill, at which the photos were taken are shown in the figure. The actual spill lasted 33 seconds and an additional approximately 12 seconds were required for vaporization to be completed. The visible cloud formed by the hydrogen spilled during the early seconds of the test was observed to rise at an angle of approximately 45 degrees, as seen in the right hand or downwind portions of the photos taken at 15, 21, and 27 seconds into the spill. As the spill progressed, the cloud formed at the spill pond began to persist at ground level to downwind distances of approximately 30 m at t = 21 seconds and 50 m

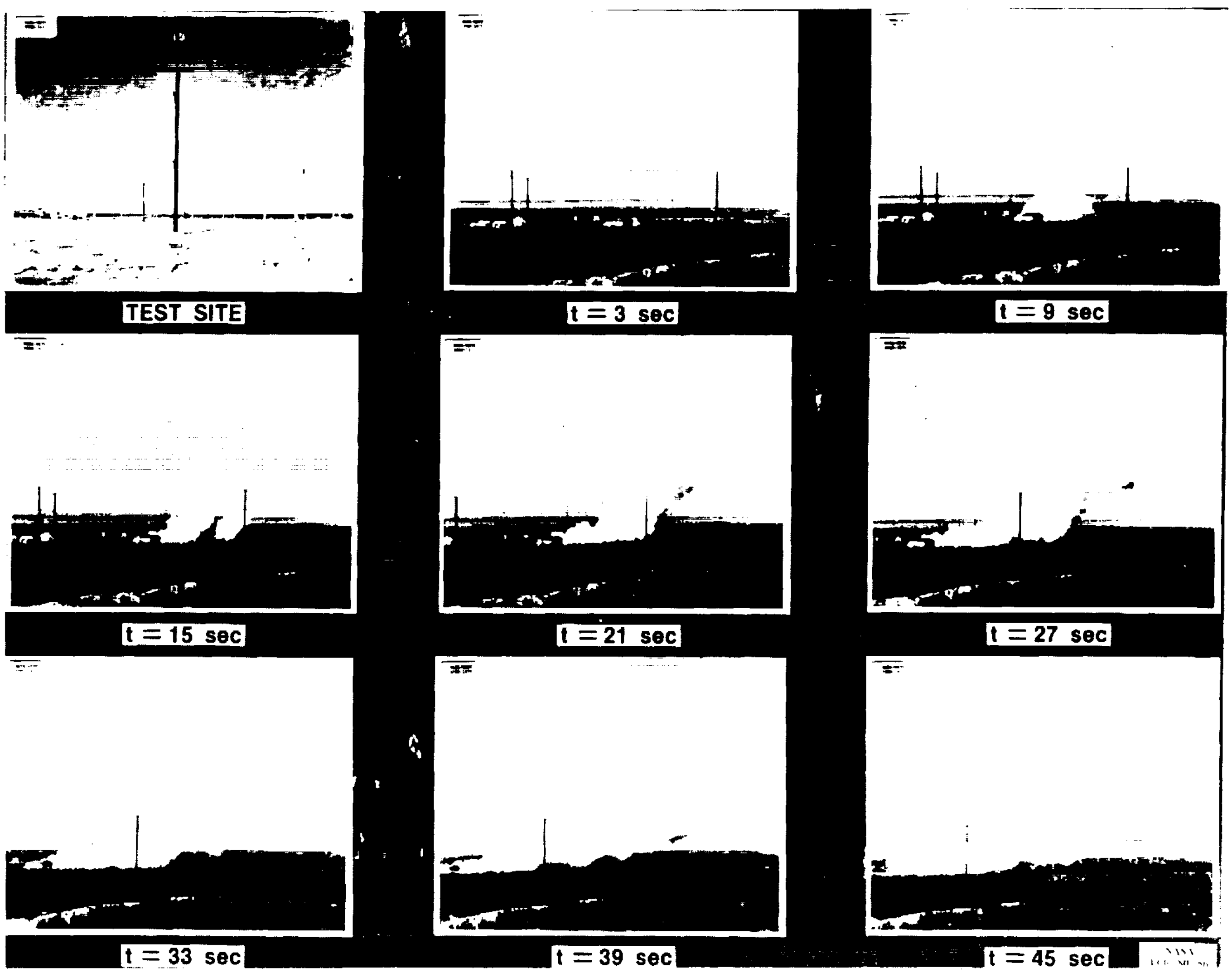

Figure 8.- Composite of photos of spill site and visible cloud from Test 4, with 3.6 m/s wind speed (t = time in seconds after start of spill).

at t = 45 seconds. The angle at which the visible cloud rose following cloud liftoff was observed to decrease from approximately 45 degrees at t = 15 to 27 seconds to 20 degrees at t = 39 and 45 seconds. The cloud rise rate at 30 and 45 seconds was approximately 0.5 m/s. Although the complete photographic history is not presented herein, the cloud was visible for approximately 80 seconds. The changes in visible cloud behavior during the test are attributed to a decrease in spill momentum due to a drop in spill line pressure following the opening of the spill line valve, and to the cooling of the ground surface in the spill pond.

Figure 9 is a composite of still photographs from Tests 2, 6, 4, and 5 during which the wind speeds were approximately 1.6, 2.2, 3.6, and 6.3 m/s, respectively. The times, after the start of the spills, at which the photos were taken are noted in the figure. These photos show the effect of wind speed on the peristence of ground-level visible cloud travel. Tests 6, 4, and 5 were characterized by a brief ground-level cloud travel (50 to 100 m) followed by a cloud rise rate of about 0.5 to 1.0 m/sec.

The abrupt cloud rise noted in the photo of Test 2 was not due solely to the lower wind speed experienced during the test. As discussed earlier, a misalinement of the spill line and the diffuser located in the spill pond (see fig 2) caused a portion of the jet from the spill line to miss the diffuser, and impact the ground with sufficient momentum as to cause the hydrogen to "bounce," and rise far more quickly than in the tests which followed. An unexpected phenonomen was observed during Test 2, in that a tornado-like vortex formed on the lower surface of the visible cloud. The remnants of this vortex can be seen just behind the pole to the right hand side of the photo of Test 2. Although there are a variety of potential explanations for the formation of the vortex. The cause has not been pinpointed.

Maximum Downwind Measured Hydrogen Concentrations

Table 3 summarizes the data from Tests 2, 4, 5, and 6, depicting the maximum downwind tower radii at which flammable hydrogen-air mixtures were measured, either by the sample bottles or the hydrogen sensors. The reader is reminded that hydrogen sensor measurements above 4 percent hydrogen are questionable, and above 8 percent are meaningless, while the sample bottle data was quite accurate and were the preferred source of data, if available. The tower heights at which these measurements were taken are also noted. Sensor data

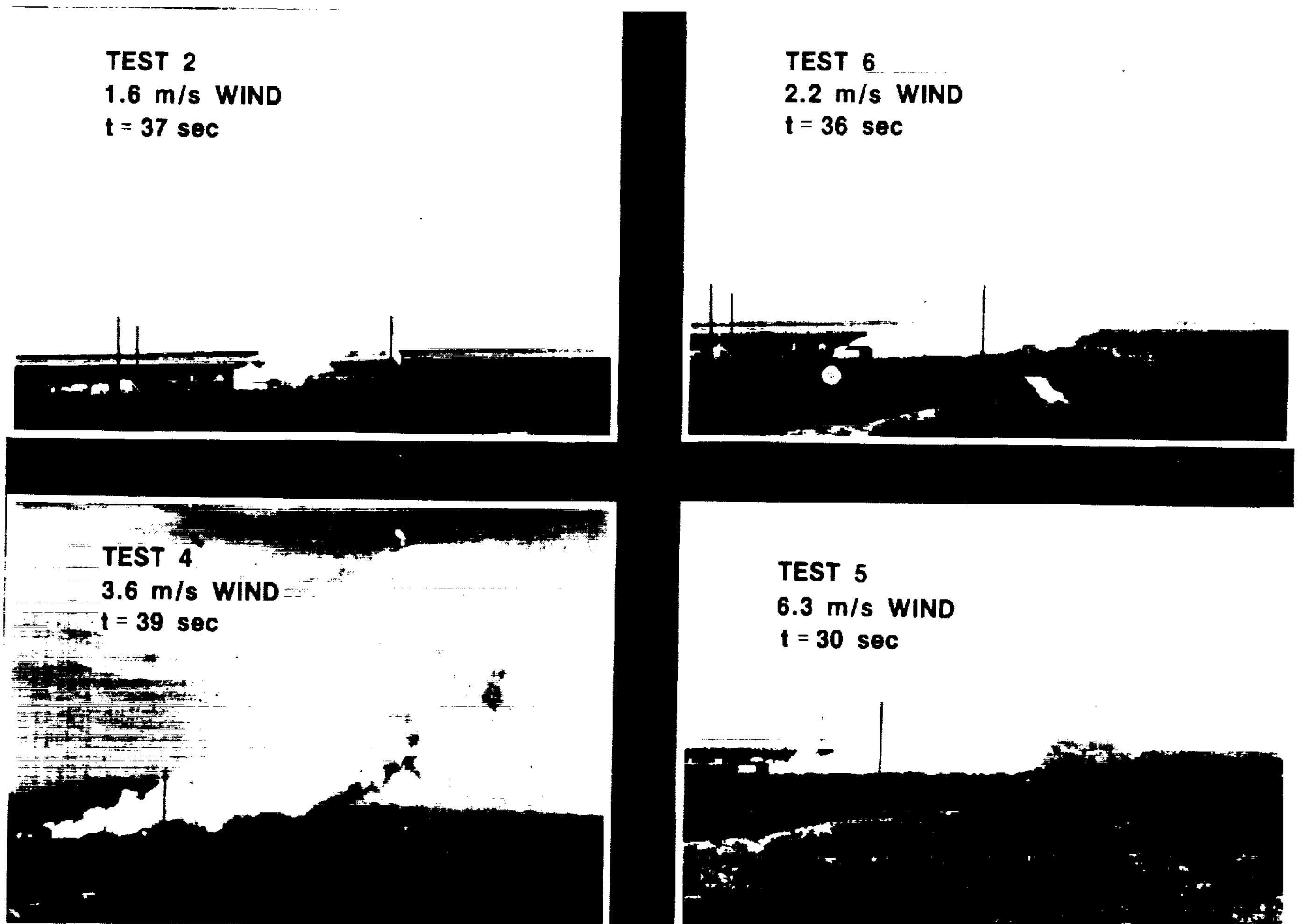

Figure 9.- Photographs of Tests 2, 6, 4, and 5 depicting wind speed effect on visible cloud travel (t = time in seconds after start of spill).

TABLE 3.- FLAMMABLE HYDROGEN CONCENTRATIONS MEASURED AT FURTHER MOST (36.6M) INSTRUMENTED TOWER

TEST	TOWER HEIGHT, m	HYDROGEN CONCENTRATION, VOL. percent	
		SAMPLE BOTTLES	SENSORS
2	1	-	-
	9.4	-	-
	18.6	-	≈6
4	1	-	-
	9.4	4	≈7
	18.6	-	≈4
5	1	-	-
	9.4	29	≈6
	18.6	-	-
6	1	-	-
	9.4	19	≈8
	18.6	19	≈4

from Test 2 indicated that a hydrogen concentration of at least 6 percent existed at a height of 18.4 m on one of the furthermost towers. As a result of a data system malfunction which occurred during Test 2, the sample bottles at that location did not open, and no quantitative concentration data above 4 to 6 percent was obtained. The data of Test 4 indicated a near flammable cloud at the 9.4 m and 18.6 heights. The data for Test 5 indicated that hydrogen concentrations as high as 29 percent passed through the 9.4 m height, but flammable concentrations were not detected at the 1 m or 18.6 m heights. The data of Test 6 indicated that hydrogen concentrations as high as 19 percent passed through the 9.4 m and 18.6 m heights, but flammable concentrations were not detected at the 1 m level.

Flammable concentrations were not measured at the 1 m height of the furthermost towers which indicates that although the visible cloud persisted at ground level (see fig 9), the lower portion of the cloud was not flammable. This is obviously contradictory to the assumption stated earlier, that the edge of the visible cloud defined the flammable boundary of the cloud. This discrepancy is yet to be resolved. Had one or more similar spills been intentionally ignited, the relevance of the theoretical calculations and the measured concentrations would have been put into better perspective.

Cloud Dispersion

As mentioned previously, a smoke grenade was used to verify that the local wind direction was suitable for conduct of a spill. The smoke plume was also observed to aid in characterizing the atmospheric turbulences at the test site. A comparison of the observed smoke plume and the pretest UVW turbulence indicator data with the observed hydrogen cloud turbulence, the UVW data taken during the spill, and the violent fluctuations of temperature within the cloud has indicated that the turbulence generated by the momentum of the spill, the rapid expansion from a liquid to a gas, and thermal instabilities in the cloud created turbulence levels far greater than those associated with the normal atmospheric turbulence experienced at the test site. Efforts are currently under way to derive dispersion coefficients from the hydrogen concentration data obtained during the experiments, and to apply those coefficients to appropriate dispersion models. Unfortunately, the results of this particular effort are incomplete and cannot be included in this paper.

Whether the results will be applicable to spills much larger than 5.7 m^3 is a moot question.

Prolonged Spills

Prior to the conduct of the recent liquid hydrogen spill experiments, it was recognized that pipeline ruptures might present a situation where extended ground-level travel of a flammable cloud could occur. A motion picture of simulated pipeline rupture tests which were conducted in the late 1950's by the A. D. Little Company (3), showed a visible cloud extending along the ground for distances well in excess of 100 m. The pipeline spill rate was on the order of several hundred of gallons per minute. The cloud was intentionally ignited proving that a large portion of the cloud was flammable. Tests 3 and 7 of the recently completed NASA experiments tend to confirm this cloud prolonged ground-level cloud behavior for slower, pipeline rupture type spills. As mentioned previously, in Tests 3 and 7, the liquid hydrogen was intentionally released at a relatively slow spill rate. The spill times for these were 85 and 240 seconds, respectively. Motion pictures were utilized to deduce hydrogen concentrations from Test 3, which missed the instrumentation towers. The dew point was calculated based on ambient temperature and relative humidity, and, assuming that the edge of the visible cloud corresponded to the dew point temperature. The hydrogen concentration at the edge of the cloud was calculated by assuming adiabatic mixing of the cold hydrogen vapors with ambient air. The results indicated that a flammable cloud existed close to the ground at a distance of some 120 m from the spill site. The data package thermocouples, hydrogen sensors, and motion picture from Test 7 indicated that, for slow spills, a flammable cloud could existed at ground level well beyond the range of the instrumentation towers, and that the turbulence levels in the cloud are more akin to those associated with normal atmospheric turbulence.

In an actual pipeline rupture, conditions could be aggravated by the orientation of the pipeline, particularly if the pipeline were parallel to the ground, and the liquid hydrogen were released <u>with</u>, or in the same direction as the wind. Pipeline pressure, which in the case of storage facilities, is generally quite modest and is produced by pressurization of a storage vessel, would quickly drop, decreasing the momentum induced turbulence associated with the spill. As the spill continued at a moderate rate, the ground would become chilled, thus decreasing the heat transfer to the liquid (heat transfer from the ground <u>is</u> the major factor in vaporization), thus reducing thermally induced turbulence.

Available evidence indicates that the occurrence of pipeline ruptures at liquid hydrogen facilities may result in significant ground level flammable cloud travel. Such potential hazards can be scoped only by additional experimental work.

Diking of Liquid Hydrogen Storage Facilities

Liquified natural gas storage facilities are generally required by law to be provided with dikes to retard the spread of the liquid and to retard the vaporization rate (4). The rationale behind the retardation of the vaporization rate is to minimize the size, at any time, of the flammable vapor cloud which must be dispersed to nonflammable concentrations. The high levels of spill and vaporization induced turbulence observed in the recently completed rapid liquid hydrogen spill experiments, were found to be most beneficial in quickly mixing the flammable cloud with air, warming the cloud, and making it bouyant. Therefore, a tentative major finding of the experiments is that the use of dikes around liquid hydrogen storage facilities would probably enhance prolonged ground level flammable cloud travel and that it may be preferable not to use dikes and to take advantage of the dispersion mechanisms provided by spill and vaporization induced turbulence.

INTERIM CONCLUSIONS

Based upon the liquid hydrogen spill quantities, rates, and modes reported herein, and upon the limited data analyses conducted thus far, the following conclusions are drawn.

Rapid liquid hydrogen spills of the type which might occur as the result of a rupture of a storage facility are characterized by a brief period of ground-level flammable cloud travel during which the violent turbulence generated by the momentum of the spill, the quick change of phase from a liquid to a vapor, and thermal instability in the cloud causes the hydrogen vapors to mix quickly with air, disperse to nonflammable concentration, warm up, and become positively buoyant. Ground-level cloud travel was found to extend approximately 50 to 100 m, followed by a 0.5 to 1.0 m/s cloud rise rate.

Prolonged, gentle spills, or spills of the type which might occur as the result of a rupture of a liquid hydrogen pipeline are characterized by prolonged ground-level cloud travel. Prolonged ground-level cloud travel is caused by reduced spill or momentum induced cloud turbulence, and is suspected to be aggravated by long term cooling of the ground which is the major heat transfer mechanism for determining evaporization rate.

Whereas liquefied natural gas storage facilities are generally required by law to include liquid containment dikes, the results of the current experiments indicate that one would be better advised not to dike liquid hydrogen storage facilities, and take advantage of spill and vaporization induced turbulent mixing with ambient air.

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